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Are Speech Perception Deficits Associated with Developmental Dyslexia?

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Phonological awareness and phoneme identification tasks were administered to dyslexic children and both chronological age (CA) and reading-level (RL) comparison groups. Dyslexic children showed less sharply defined categorical perception of a *bath–path* continuum varying voice onset time when compared to the CA but not the RL group. The dyslexic children were divided into two subgroups based on phoneme awareness. Dyslexics with low phonemic awareness made poorer /b/–/p/ distinctions than both CA and RL groups, but dyslexics with normal phonemic awareness did not. Examination of individual profiles revealed that the majority of subjects in each group exhibited normal categorical perception. However, 7 of 25 dyslexics had abnormal identification functions, compared to 1 subject in the CA group and 3 in the RL group. The results suggest that some dyslexic children have a perceptual deficit that may interfere with processing of phonological information. Speech perception difficulties may also be partially related to reading experience.

Children identified as dyslexic have difficulties learning to recognize printed words and perform poorly on related tasks such as pronouncing nonsense words and spelling (Bruck, 1990; Rack, Snowling, & Olson, 1992; Stanovich, 1988; Vellutino, 1979). According to one view, the phonological deficit hypothesis, the reading and spelling impairments are related to specific deficits in the representation and use of phonological information. The phonological deficit limits dyslexic children's ability to learn print–sound correspondences, an important step in learning to read (Jorm & Share, 1983; Liberman & Shankweiler, 1985; Rack et al., 1992; Stanovich, 1988; Wagner & Torgesen, 1987). Phonological deficits have been demonstrated in three broad areas (Wagner & Torgesen, 1987): phonological awareness (Bradley & Bryant, 1978; Bruck, 1992; Manis, Custodio, & Szeszulski, 1993), phonological recoding in lexical access (Bowers & Swanson, 1991; Denckla & Rudel, 1976; Wolf, 1986), and phonological recoding in working memory (Byrne & Shea, 1979; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979).

There is considerable evidence that deficits in phonological awareness are related to problems in learning to read. Several prospective longitudinal studies suggest a causal link between sensitivity to the phonological structure of words and later progress in reading acquisition (Bryant, Maclean, Bradley, & Crossland, 1990; Lundberg, Olofsson, & Wall, 1980; Stanovich, Cunningham, & Cramer, 1984), although the relationship between reading and phonological awareness is probably reciprocal (Morais, Bertelson, Cary, & Alegria, 1979; Perfetti, Beck, Bell, & Hughes, 1987; Wagner, Torgesen, & Rashotte, 1994). Studies in which children were trained on phonemic awareness, phoneme segmentation, and blending provide evidence of moderate improvements in reading, especially if explicit linkages between phonemes and printed letters are made (Bradley & Bryant, 1985; Hatcher, Hulme, & Ellis, 1994; Lundberg, Frost, & Peterson, 1988). Finally, phonological deficits persist over time in dyslexic children (Manis et al., 1993; Wagner et al., 1994), even into adulthood (Bruck, 1992; Masterson, Hazan, & Wijayatilake, 1995).

Why do children who later become poor readers have difficulty analyzing the phonological structure of spoken words? One possibility is that they have inadequate representations of phonemes stemming from a basic perceptual deficit (Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Reed, 1989; Tallal, 1980). Distorted, degraded, partially specified, or otherwise deficient phonological representations could be expected to interfere with or delay the process of becoming phonemically aware, which in turn can lead to problems in learning spelling-to-sound correspondences (Reed, 1989; Share, 1995; Wagner & Torgesen, 1987). Deficient phonological representations might also underlie reader-group differences in phonological recoding in lexical access (e.g., Denckla & Rudel, 1976; Wolf, 1986) and phonological recoding in working memory (e.g., Byrne & Shea, 1979; Shankweiler et al., 1979).

Do dyslexic children have a deficit in identifying and discriminating phonemes in speech? The consensus has been that they do, but the deficit is small (McBride-Chang, 1995a; Werker & Tees, 1987). Approximately 20 published studies have examined speech perception in dyslexic children and adults. Two major experimental paradigms have been used, categorical perception of stop consonants, such as /b/, /d/, /g/, and /p/, and repetition of speech with and without noise. The categorical perception experiments are based on the general principle that although acoustic variations in speech are continuous (such as the delay in voicing that differentiates /b/ and /p/ in English), people tend to perceive them as discontinuous. For example, /b/ and /p in English differ along a continuum of voice onset time (VOT). Adult speakers of English demonstrate a perceptual boundary between /b/ and /p/ at about 25–35 ms of voicing delay (Miller, Green, & Schermer, 1984). Differences between dyslexics and age-matched controls in categorical perception of several consonant continua have been reported for samples of children (Godfrey et al., 1981; Reed, 1989; Werker & Tees, 1987) as well as adults (Lieberman, Meskill, Chatillon, & Schupack, 1985; Steffens, Eilers, Gross-Glenn, & Jallad, 1992; Watson & Miller, 1993). In addition to the differences in perception of artificially produced speech continua, Reed (1989) found that dyslexic children were less able than normal readers to discriminate naturally produced words that differed only in their initial phoneme. The reader-group difference in discrimination of natural speech tokens was replicated by Masterson et al. (1995). Other studies have obtained nonsignificant results in some conditions or with some groups of subjects (Brandt & Rosen, 1980; De Weirdt, 1988; Hurford & Sanders, 1990). For example, Hurford and Sanders (1990) obtained a significant difference in discrimination of CV syllable pairs (/gi/–/gi/ vs /gi/–/bi/) for second-grade good and poor readers but not for fourth graders. Even in studies failing to find a significant difference, dyslexic children have tended to be less clear in discriminating sounds across phonological categories and in identifying speech sounds at the end points of a continuum (McBride-Chang, 1995a; Reed, 1989; Werker & Tees, 1987). The pattern of group differences is fairly consistent across studies, even if the differences are not statistically significant in some studies.

The speech repetition experiments ask subjects to repeat words or nonwords immediately after hearing them. The words are played under normal conditions or with a partial white-noise mask. Brady, Shankweiler, and Mann

(1983) played high- and low-frequency words for third-grade good and poor readers. Half of the stimuli had white noise superimposed over the original recording and half were presented without noise. Poor readers repeated the words less accurately than the good readers in the white-noise condition only. The authors argued poor readers were capable of recognizing and repeating the words, but due to a subtle speech perception deficit, they were less accurate in doing so under conditions of noise. Two studies failed to find reader-group differences in word repetition under noise conditions with children (Snowling, Goulandris, Bowlby, & Howell, 1986) and with adults (Pennington, Van Orden, Smith, Green, & Haith, 1990). However, Snowling et al. (1986) did find differences in repetition of monosyllabic nonwords and low-frequency real words in noise. They argued that difficulties in phoneme segmentation, rather than speech perception, might be primary. Other studies using clear speech have found reader-group differences in repetition of multisyllabic real words (Brady, Poggie, & Merlo, 1986) and repetition of multisyllabic nonwords (Kamhi & Catts, 1986; Kamhi, Catts, & Mauer, 1990). Particularly in the case of multisyllabic items, speech repetition difficulties could be due to problems in storage and retrieval of verbal codes (Catts, 1989). Taken together, the speech repetition studies provide only suggestive evidence of reader-group differences in speech perception.

An interesting variation on the speech repetition experiments was reported by Reddington and Cameron (1991). They presented dyslexic and normally reading children with monsyllabic words at varying levels of sound intensity to determine the lowest level at which the children could accurately repeat the words. Dyslexics' average auditory threshold was 7.5 dB higher than the control group, which means that dyslexics needed approximately twice the level of sound in order to repeat back monosyllabic words. None of the children was reported to have a hearing problem. However, the reader-group difference was accounted for by 5 of the 17 cases. There were no reader-group differences in word repetition at 35 dB above individual threshold levels. The authors suggested that speech-processing deficits are found in some but not all dyslexics.

There are two main explanations for the mixed pattern of speech-perception results. First, the differences are real, but small and therefore hard to detect. According to Werker and Tees (1987), small differences in speech perception might have considerable significance for learning to read. If phonological categories are less robust among dyslexic children, they would be more prone to disruption under stress, such as occurs during the challenging period of beginning reading, when children must not only become familiar with the orthographic conventions of their language, but also segment spoken words into phonemes and learn grapheme–phoneme correspondences. From this perspective, it would not be surprising if children with subtle speech perception problems had difficulties on tests of phonological awareness. Phonological-awareness tasks require a more explicit level of awareness of the phoneme than speech perception tests, as subjects are generally asked to count, delete, or otherwise manipulate specific phonemes within a spoken word, rather than simply to discriminate between two phonemes (Stahl & Murray, 1994; Yopp, 1988). The phoneme-awareness tasks would put severe stress on fragile phoneme-identification skills. In support of this hypothesis, several studies have found associations between speech perception and phoneme awareness. Hurford (1991) obtained a moderate correlation between phoneme-segmentation ability and speech discrimination in elementary school children. Flege, Walley, and Randazza (1992) reported a link between perception of vowels and two measures, phoneme segmentation and rhyming, in 4- to 12-year-olds. Eisen, Fowler, and Brady (1995) also found an association between perceptions of fricative vowel syllables and phonological awareness in kindergartners. Finally, McBride-Chang (1995b) obtained a significant correlation between speech perception and phonological awareness in a large, unselected sample of third- and fourth-graders.

A second explanation for the mixed pattern of results is that the group comparisons in past studies mask larger speech-perception deficits that are found in only a subgroup of dyslexics. One widely recognized distinction is between phonological and nonphonological subtypes of dyslexia (Boder, 1973; Castles & Coltheart, 1993; Mitterer, 1982; Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996; Murphy & Pollatsek, 1994; Seymour & MacGregor, 1984). Phonological dyslexics have severe nonword reading problems and make many phonological errors in reading. Nonphonological (sometimes called ‘‘surface’’) dyslexics have less marked nonword reading problems, but have difficulty recognizing words that do not follow regular spelling–sound correspondence rules. Manis et al. (1996) showed that children on the phonological dyslexic end of the continuum were impaired on a phonological awareness task, whereas children on the surface dyslexic end did not differ from age-matched controls. If some dyslexic children read poorly, but have normal phonological awareness, it is possible that speech perception would be normal in this segment of the dyslexic population, resulting in a smaller overall group difference. Furthermore, the size of the group difference might vary depending on the proportion of phonological dyslexics in the sample.

Godfrey et al. (1981) attempted to investigate subgroup differences in speech perception using the dysphonetic/dyseidetic classification system of Boder (1973). Performance on speech perception tasks showed equal (and small) impairments for both subgroups. However, their dyseidetic group was small ($n = 6$) and Boder’s method of identifying subgroups may be imprecise, as it relies on a questionable analysis of phonetic accuracy in spelling (Moats, 1993). Hence, the question of individual differences in speech perception within the dyslexic population remains largely unexplored.

Even when group differences in speech perception are obtained, the interpretation of the difference is complicated by the fact that speech perception has been assessed using a variety of tasks that differentially tax short-term memory (McBride-Chang, 1995b; De Weirdt, 1988). This is a potentially significant factor in a population of children such as dyslexics, who tend to have difficulty on short-term memory tasks (e.g., Byrne & Shea, 1979; Shankweiler et al., 1979). The identification paradigm used in categorical speech perception studies probably places a smaller burden on memory than any of the alternative paradigms. Subjects are presented with a single stimulus from a continuum (e.g., /ba/–/pa/) and are then required to identify it, either by repeating it out loud or by otherwise selecting it from among a limited number of alternatives. The next highest memory demands probably occur for speech repetition in noise, since the subject is required to recode phonetically an entire word or nonsense word rather than a short syllable. Higher memory demands are made in the AX and ABX discrimination paradigms and in discriminating pairs of natural speech tokens differing in initial consonant. In an AX experiment, subjects first listen to paired stimuli typically separated by about 1 s (e.g., /ba/–/da/). They must then report whether or not the two stimuli were identical. In an ABX paradigm, subjects are first presented with three stimuli (e.g., /ba/–/da/–/da/). They are then required to indicate whether the third stimulus sounded more like the first or second stimulus. These two paradigms require that exact phonetic codes be maintained in memory and compared to one another over brief periods of time.

Reader-group comparisons using the identification or speech repetition paradigms have tended to yield smaller reader-group differences (e.g., De Weirdt, 1988; Godfrey et al., 1981; Lieberman et al., 1985; Reed, 1989; Snowling et al., 1986; Werker & Tees, 1987) than those using various discrimination paradigms (De Weirdt, 1988; Godfrey et al., 1981; Reed, 1989; Werker & Tees, 1987). The smaller effects may be due to the greater memory demands of the discrimination tasks. Smaller effects for the identification paradigm could also be due to the fact that discrimination tasks require more fine-grained discriminations, making them more sensitive to potential perceptual differences among reader-ability groups.

The purpose of the present study was to investigate possible speech perception deficits in dyslexic children. The identification paradigm was used in order to minimize memory demands. Of particular interest was an examination of individual differences in speech perception. To explore individual differences, dyslexics were divided on the basis of scores on a phonological awareness task. The study also featured a design element not present in most past studies of speech perception, a reading-level comparison group. The inclusion of younger normal readers matched on reading level to the dyslexics allows a test of the hypothesis that speech perception deficits in past studies might be due to differences in reading experience or reading grade levels, rather than reader group status itself.

METHOD

Subjects

Dyslexics. Twenty-five students in grades 4 through 10 participated in the study. Subjects were obtained by referral from special education or remedial reading classes at two public elementary schools, two public middle schools, and one private school. The private school was a special school for children with learning disabilities that served children in grades 4 through 12. Twenty-eight students were referred from the private school and 9 from the public schools. Of the 37 students who were referred, 25 were classified as dyslexic based on three criteria: (a) a reading score at or below the 25th percentile on the Word Identification subtest of the Woodcock Reading Mastery Test–Revised (Woodcock, 1989), (b) a WISC-III composite cognitive ability scaled score of 86 or higher, and (c) a Woodcock score that was 12 or more standard score points below the WISC-III composite (equivalent to a $\frac{3}{4}$ standard deviation discrepancy). WISC-III composite scores were obtained from four subtests of the WISC-III: Vocabulary, Similarities, Block Design, and Picture Completion (Wechsler, 1992). The sex ratio was 22 males to 3 females. The ethnic composition of this group was 23 Caucasian, 1 Asian, and 1 African-American.

Chronological age comparison group. Twenty-five students in grades five through eight participated in the study. The subjects were selected using the following procedure: 35 students were selected at random from a pool of over 600 students at the same four public schools used to obtain the dyslexic sample. Ten of these students were disqualified, based on reading scores below the 50th percentile or estimated WISC-III scores outside the range for the dyslexics (86–130), resulting in a group size of 25. The sex ratio was 14 males to 11 females for this group. The ethnic composition was 18 Caucasian, 6 Asian-American, 1 African-American, and 2 Hispanic.

Reading-level comparison group. Twenty-four subjects in grades two and three participated in the study. Children in this group were selected at random from a pool of over 200 students at the two elementary schools used above. An initial sample of 35 students was selected at random from the larger pool. Eleven of these students were disqualified, based on reading scores below the 50th percentile or WISC-III composite scores outside the range for the dyslexics (86–130), resulting in a group size of 24. The sex ratio was 16 males to 9 females for this group. The ethnic composition was 18 Caucasian, 3 Asian, 2 African-American, and 1 Hispanic.

None of the children in the three groups had been classified by their schools as emotionally disturbed, according to teacher reports. In addition, none of the children had significant hearing difficulties on the audiometric screening test given by the schools. According to parent reports, available on 86% of the subjects, one child in the CA group and one in the dyslexic group had partial hearing loss in one ear. Three children in the CA group, two in the RL group, and two in the dyslexic group had a history of severe ear infections, which had resolved.

Procedure

Subjects were tested individually in a quiet room at their schools during school hours. Testing took place in three sessions spaced approximately one week apart. Each session lasted approximately 45 min. The following tasks were administered to the children:

Word Identification subtest of the Woodcock Reading Mastery Test–Revised (Woodcock, 1989) (form H). This test requires children to read a list of words out loud until the children reach a ceiling level (six misses in a row), at which time the test is discontinued. The split-half reliability of this measure ranges from .86 to .99 for children in grades 3 through 11 (Woodcock, 1989).

Word Attack subtest of the Woodcock Reading Mastery Test–Revised (Woodcock, 1989) (form H). This test requires children to read nonsense words out loud until they reach a ceiling level where their responses are no longer phonemically correct. The split-half reliability of this measure ranges from .84 to .91 for children in grades 3 through 11.

WISC-III composite ability score. Four subtests of the Wechsler Intelligence Scale for Children-III (Wechsler, 1992) were administered to the children in order to obtain a composite cognitive ability score. These subtests were Picture Completion, Similarities, Block Design, and Vocabulary. The composite cognitive ability score was obtained by summing the four subtest standard scores and dividing by 0.4 to put it on the same scale as the IQ (mean of 100 and standard deviation of 15). This score, of course, only approximates the full scale IQ and its purpose was to obtain a measure of general cognitive ability.

Position analysis. Position analysis was a task assessing phonological awareness that was developed by Manis et al. (1996) based on phoneme isolation tasks utilized by Yopp (1988) and Stahl and Murray (1994). Subjects were required to listen to a nonsense word spoken aloud by the experimenter and repeat it back to ensure that they had perceived it correctly. The experimenter then pronounced a specific phoneme contained in the nonsense word and asked the subject to produce the phoneme that came immediately before or immediately after the target phoneme (e.g., ''Say /nolf/. Which sound comes after the /l/ sound in /nolf/?''). No right/wrong feedback was given. On half of the trials, the sound came before and on half it came after the target phoneme. The format of the position analysis task was ideal for the present purposes because it required subjects to recognize phonemes in the context of other phonemes in a spoken stimulus, a task requiring the generation of high-quality phonemic representations, as well as various operations on the phonemic representations (e.g., segment phonemes, maintain items in correct order in memory, etc.). The task was 24 trials in length and had an internal consistency reliability (using the coefficient alpha method) of 0.85, calculated for the present sample.

Phoneme identification task. Categorical speech perception was assessed by asking children to identify instances of the words bath and path. The bath–path stimuli were created by Miller, Green, and Schermer (1984) who used them in studies of adults. The stimuli were made by editing natural instances of the words bath and path produced by a male speaker articulating a sentence at a moderate rate (''She is not thinking of the bath/path'').

The natural speech tokens of bath and path were used to construct a 13-member series, in which the change from /b/ to /p/ was accomplished by varying the voice onset time (VOT) for the initial stop consonant in each word. VOT is defined in articulatory terms as the time between the release of lip closure and the onset of vocal cord vibration (Abramson & Lisker, 1970; Lisker & Abramson, 1964). It is measured acoustically as the time between the abrupt increase in energy at the consonantal release and the onset of vocal cord vibration. VOT is typically shorter for voiced than for voiceless stops. The original values of VOT in the natural speech samples were 0 ms for bath and 73 ms for path. A 13-member continuum was created by replacing successively larger voiced acoustic segments from the naturally recorded instance of bath, beginning at the end of closure for /b/, with equally long unvoiced acoustic segments taken from the natural instance of path, beginning at the end of closure for /p/. In other words, a series of VOT values were created, holding the other sounds in the word *bath* constant. The 13 VOT values used in the experiment were: 7, 12, 15, 19, 21, 26, 32, 35, 39, 45, 48, 53, and 59 ms. Although these stimuli were computer-edited hybrid words, they were consistently perceived as unedited tokens of natural speech by naive listeners (Miller et al., 1984). The total duration of each stimulus was 418 ms. The stimuli were digitized at 8 bits and 22 kHz and stored on disk. They were played through a 5-in. speaker connected to the audio output jack of a Macintosh Classic II computer.

The speech stimuli were presented one at a time. Children were instructed to listen carefully to each sound stimulus. On each trial, the stimulus would play while the two word choices *bath* and *path* were displayed on the computer screen. *Bath* was always on the left and *path* was always on the right. Children then pressed one of two buttons to indicate their word choice for that trial. It might be objected that the response demands of reading printed words put the dyslexics at a disadvantage. However, pilot data indicated that dyslexic children had no difficulty reading the two response choices on the screen. In addition, during the instructions for the experiment, children were asked to say which of the printed words was ‘‘bath’’ and which was ‘‘path,’’ and all but one of the children, a dyslexic, could read both words. The child who made the error was corrected and had no difficulty after that point. Hence, though it is possible that poor readers could intermittently become confused, this seems unlikely, as the words were printed in large, boldface type, always occupied the same spatial position on the screen, and could in fact be discriminated by reading only the first letter.

Each of the 13 points on the continuum was randomly administered eight times for a total of 104 trials. An identification function was created for each child by graphing the percent of path responses as a function of VOT (7 through 59 ms). Individual slope values for this function were the units of analysis for this task. These slopes were derived using logistic regression, in which the 13 points on the continuum (conceptualized as representing a single continuous variable) were used to predict the percentage of *path* responses across the eight trials at each VOT. The internal consistency reliability (split-half reliability) for the slope measure was .75.

RESULTS

Results for the psychometric and experimental measures are presented in Table 1 for the three reader-groups. The CA group was 12.0 years old on average, the dyslexics averaged 13.3 years of age, and the RL group 8.5 years of age. Most comparisons in the study were conducted with *t* tests. The *t* values and degrees of freedom were adjusted for unequal variance between groups where applicable. Dyslexics were significantly older than both the CA group, $t(40) = 3.17$, $p < .01$, and the RL group, $t(30) = 12.63$, $p < .0001$. The dyslexics did not differ reliably in WISC-III ability from either the CA group or the RL group, although the difference with the RL group approached significance ($p < .07$). On the selection measure (Woodcock Word Identification grade equivalent), dyslexics had a very similar mean and did not differ statistically from the RL group, but were by definition much lower than the CA group, $t(30) = 8.27$, $p < .0001$.

As anticipated, the dyslexics were much poorer as a group than the CA group on position analysis, $t(32) = 3.68$, $p < .001$, and Word Attack, $t(29) = 14.4$, $p < .0001$, in keeping with previous studies showing a deficit in phonological processing among dyslexics (Bradley & Bryant, 1978; Bruck, 1992; Manis et al., 1993; Rack et al., 1992). The dyslexics performed more than five grade levels below the RL group on Word Attack, a significant difference, $t(25) = 4.05$, $p < .0001$. However, the dyslexics did not differ from the RL group on position analysis even though differences were in the predicted direction (dyslexics lower). There was considerable variability within the dyslexic group but clearly the sample as a whole was not as severely impaired in phonemic awareness as samples in some previous studies where differences with an RL group were found (e.g., Bradley & Bryant, 1978; Bruck, 1992; Manis et al., 1993).

The phoneme-identification functions for the three reader-groups are shown in Fig. 1. Averaged across individuals, the functions are very regular, with short VOT values associated with *bath* and long VOT values associated with *path*. All three groups showed a relatively sharp change, from *bath* to *path* at about 21–26 ms of voicing delay. The dyslexics had a shallower slope than the CA group, $t(40) = 2.27$, $p < .05$, reflecting a weaker categorical distinction between /b/ and /p/. The dyslexics also showed a shallower slope than the RL group, but this difference was not statistically reliable. As can be seen in Fig. 1, the dyslexics' function did not show as sharp an increase from the /b/ end to the /p/ end of the continuum as the normal reader-group's functions; thus, more dyslexics identified clear instances of /b/ as /p/ and vice versa than was the case for the CA and RL groups.

Because of the interest in determining whether subgroups of dyslexics varying in phonological skill would show different degrees of difficulty in speech perception, correlational and subgrouping analyses were conducted.

TABLE 1
Basic Statistics on All Relevant Measures for Normal Readers and Dyslexics

Variable	CA group (n = 25)		Dyslexics (n = 25)		RL group (n = 24)	
	Mean (*SD*)[a]	Range	Mean (*SD*)[a]	Range	Mean (*SD*)	Range
Age (in years)	12.0 (1.1)	10.0 to 14.3	13.3 (1.8)	10.1 to 15.9	8.5 (0.6)	7.6 to 10.2
WISC-III Ability[b]	107.1 (10.9)	86 to 124	102.6 (11.5)	86 to 124	108.3 (9.4)	90 to 126
Pos. analysis[c]	21.3 (2.0)	17 to 24	17.4 (4.9)	8 to 24	19.3 (3.8)	13 to 24
Word Iden. SS[d]	114.0 (7.2)	100 to 129	72.2 (14.5)	32 to 90	111.5 (8.6)	100 to 127
Word Iden. GE[e]	10.2 (2.1)	7.1 to 16.9	4.2 (1.3)	1.3 to 7.0	4.3 (1.2)	2.8 to 7.4
Word Attack SS[d]	110.6 (10.4)	78 to 128	75.9 (12.8)	47 to 92	108.7 (11.8)	88 to 126
Word Attack G.E.[e]	14.9 (3.9)	4.2 to 16.9	3.0 (1.3)	1.0 to 5.9	8.1 (6.1)	2.2 to 16.9
/b/–/p/ slope	−1.1 (0.7)	−3.0 to −0.4	−0.8 (0.4)	−1.7 to −0.1	−1.0 (0.8)	−3.0 to −0.2

[a] *SD*, Standard deviation.
[b] Wechsler Intelligence Scale for Children-III Composite Ability based on four subtests.
[c] The total possible correct was 24 on this task.
[d] Woodcock Word Identification and Woodcock Word Attack Standard Scores.
[e] Woodcock Word Identification and Woodcock Word Attack Grade Equivalent Scores.

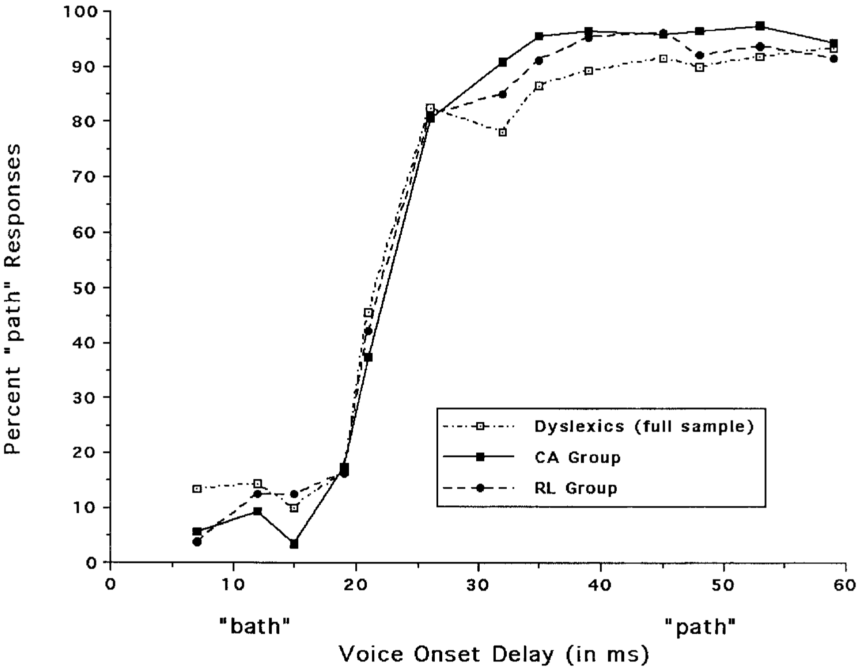

FIG. 1. /b/–/p/ identification functions for the CA and RL groups and the full sample of dyslexic children.

The correlations among the key variables in the study are shown in Table 2 for the sample as a whole. Of particular interest is the correlation between position analysis and slope scores. The size of the correlation is moderate ($r = -.30$) but significant with a sample size of 74 ($p < .025$). Word Identification grade level scores were also moderately correlated with slope ($r = -.26$,

TABLE 2
Correlations for the Full Sample

Variable	1	2	3	4	5	6
1. Grade						
2. WISC-III Ability	−.10					
3. Woodcock Word Iden. G.E.	.29	.27				
4. Woodcock Word Attack G.E.	−.02	.30	.82			
5. Position analysis	−.01	.29	.53	.63		
6. /b/–/p/ identification slope	−.01	−.16	−.26	−.20	−.30	

Note. Correlations of .24 and above were significant at the .05 level and correlations above .30 were significant at the .01 level ($n = 74$).

TABLE 3
Means and Standard Deviations[a] on All Relevant Measures for Normal Readers and the High and Low Phonological Awareness Dyslexic Subgroups

Variable	CA group	Dyslexic high phon. group	Dyslexic low phon. group	RL group
Age (in years)	12.0 (1.1)	13.6 (1.6)	13.0 (1.9)	8.5 (0.6)
Est. WISC-III IQ	107.1 (10.9)	107.2 (12.1)	98.3 (9.5)	108.3 (9.4)
Pos. analysis[b]	21.3 (2.0)	21.7 (1.5)	13.5 (3.1)	19.3 (3.8)
Word Iden. SS[c]	114.0 (7.2)	78.6 (10.8)	66.2 (15.4)	111.5 (8.6)
Word Iden. GE[d]	10.2 (2.1)	4.4 (1.1)	3.3 (2.2)	4.3 (1.2)
Word Attack SS[d]	110.6 (10.4)	83.3 (12.6)	75.9 (12.8)	108.7 (11.8)
Word Attack G.E.[e]	14.9 (3.9)	3.6 (1.5)	2.4 (0.8)	8.1 (6.1)
/b/–/p/ slope	−1.1 (0.7)	−0.9 (0.4)	−0.6 (0.3)	1.0 (0.8)

[a] Standard deviations are given in parentheses.
[b] The total possible correct was 24 on this task.
[c] Woodcock Word Identification Standard Score.
[d] Woodcock Word Identification Grade Equivalent Score.

$p < .025$), but Word Attack grade level, WISC-III ability, and grade in school were not.

To explore further the association between phoneme awareness and speech perception, the dyslexics were divided at their own group median on position analysis. This resulted in a subgroup ($n = 12$) which had virtually the same mean and range as the CA group on the position analysis task and a subgroup ($n = 13$) that performed considerably below the CA group. The finding that nearly 50% of the dyslexics were essentially within the normal range on a measure of phoneme awareness was unexpected given the sizable reader-group differences reported in previous studies in both our own (Manis et al., 1993) and other laboratories (e.g., Bradley & Bryant, 1978; Bruck, 1992). A possible source of the discrepancy between dyslexic samples may be the fact that the present sample was older and more highly remediated than most samples in the literature. Most subjects in this study attended a private school with a very low student/teacher ratio and many had received several years of remediation. We did not collect individual data on years of remediation, but this is a variable of interest in future studies. In addition, the measure of phoneme awareness we used may be less difficult than the tasks used in past studies, since it required only a single phoneme response.

Means and standard deviations for the two dyslexic subgroups and the CA and RL groups on the WISC-III composite score, Woodcock Word Identification and Word Attack, position analysis, and /b/–/p/ identification slope are shown in Table 3. The low phonemic awareness group (‘‘low phon. group’’) was significantly lower than the high phonemic awareness group (‘‘high phon. group’’) on WISC-III ability, $t(23) = 2.07$, $p < .05$, on Word Identification grade level, $t(23) = 2.94$, $p < .01$, and on Word Attack grade level, $t(23) =$

2.61, $p < .025$, but not on age. Given their tendency toward lower WISC-III ability, reading scores, and phonological awareness, the low phon. group could be thought of as a more impaired subset of dyslexics than the high phon. group.

The low phon. group differed from the CA group on WISC-III ability, $t(36) = 2.47$, $p < .025$, Word Identification grade level, $t(35) = 11.5$, $p < .0001$, Word Attack, $t(28) = 15.3$, $p < .0001$, position analysis, $t(36) = 9.46$, $p < .0001$, and age, $t(36) = 2.11$, $p < .05$. The high phon. group differed from the CA group on Word Identification, $t(35) = 8.8$, $p < .0001$, Word Attack, $t(34) = 12.6$, $p < .0001$, and age, $t(36) = 3.65$, $p < .001$, but not on position analysis.

The low phon. group differed from the RL group on WISC-III ability, $t(35) = 3.10$, $p < .01$, Word Attack, $t(24) = 4.54$, $p < .0001$, position analysis, $t(34) = 4.66$, $p < .0001$, and age, $t(35) = 6.43$, $p < .0001$, with dyslexics obviously being older. The two groups did not differ on Word Identification grade level. The high phon. group differed from the RL group on age, $t(35) = 5.95$, $p < .001$, and Word Attack, $t(28) = 3.42$, $p < .01$, but not on WISC-III ability, Word Identification, or position analysis. The difference on Word Attack indicates that both low and high phon. subgroups were severely impaired in nonword reading, although the low phon. group was the more impaired of the two.

The bath–path identification functions for the two dyslexic subgroups and the normal reader comparison groups are shown in Fig. 2. Comparisons of the dyslexic subgroups to each other and to the CA and RL groups were made for the key variable of /b/–/p/ identification slope. From Fig. 2, it is apparent that all four groups showed similar categorical boundaries but they differed at the end points of the continuum. The low phonological awareness group showed more confusions of /b/ and /p/ at or near the end points than any of the other groups, resulting in a lower slope value.

Because the dyslexics were older than the CA group and because the low phon. group had lower WISC-III ability scores than the other groups, age and WISC-III ability were covaried out of an analysis comparing these three groups on slope. The group difference in slope was significant, $F(2,47) = 3.60$, $p < .05$. Planned comparisons of each subgroup to the CA group by F test (covarying age and WISC-III ability) revealed that the low phon. group differed significantly on speech slope from the CA group, $F(1,36) = 6.26$, $p < .025$, but the high phon. and CA groups did not differ. The same comparisons, covarying out age and WISC-III ability, were made between the low phon. and high phon. subgroups. The difference in slope between subgroups approached significance, $F(1,23) = 3.62$, $p < .07$. Finally, planned comparisons of each subgroup to the RL group by F test (covarying WISC-III ability) showed that the low phon. group had a smaller slope than the RL group, $t(34) = 2.07$, $p < .05$, but the high phon. group and the RL group did not differ.

The finding of an association between phonological awareness and categorical speech perception led us to examine individual identification functions

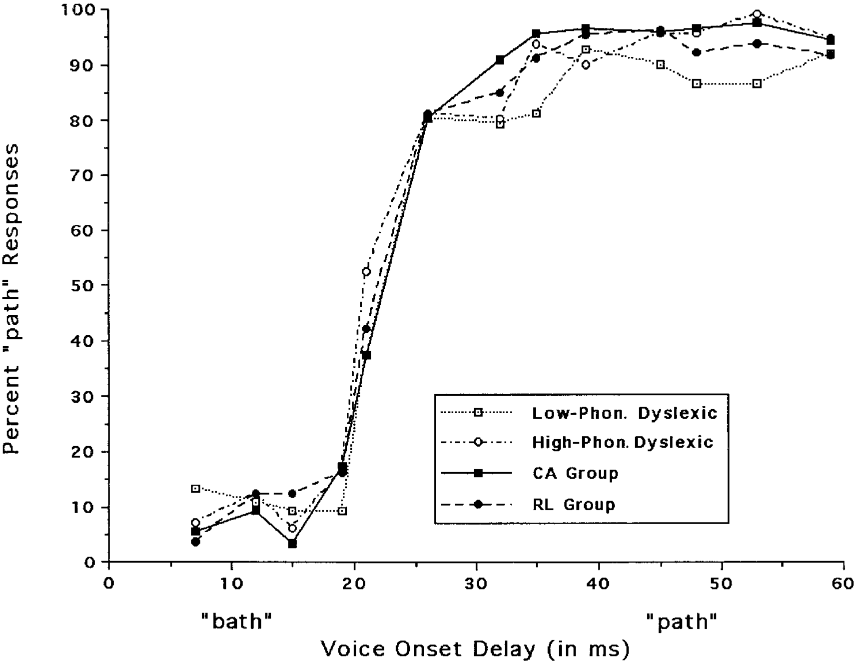

FIG. 2. /b/–/p/ identification functions for the CA and RL groups and subgroups of dyslexic children varying in phonological awareness.

for all 74 subjects. The large majority of the CA group made very sharp distinctions between stimuli at the ends of the continuum and differed only slightly in the point at which they appeared to make the transition between the /b/ and the /p/ categories. Figure 3 shows three curves from the CA group illustrating the variation in transition points. The three cases appear to have made transitions at 21, 26, and 32 ms, respectively, based on an inspection of their identification functions. These functions are very much like the standard adult functions for phoneme identification (Ganong, 1980; Lisker & Abramson, 1964; Miller et al., 1984). The only abnormalities found for any of the CA subjects involved one subject for whom the /b/–/p/ distinction was not very clear. Some confusions at the /b/ end of the continuum occurred in three cases, but these confusions were not as severe as the dyslexics discussed below and were not accompanied by confusions at the /p/ end.

Most dyslexics also made sharp categorical distinctions and did not confuse stimuli at the /b/ or /p/ ends of the continuum. This was true for the majority of the cases in both the low phonological awareness and high phon. groups. However, we identified seven cases with abnormal identification functions. These cases showed more severe confusions and identification problems than any of the subjects in the CA group. Because these seven cases were largely

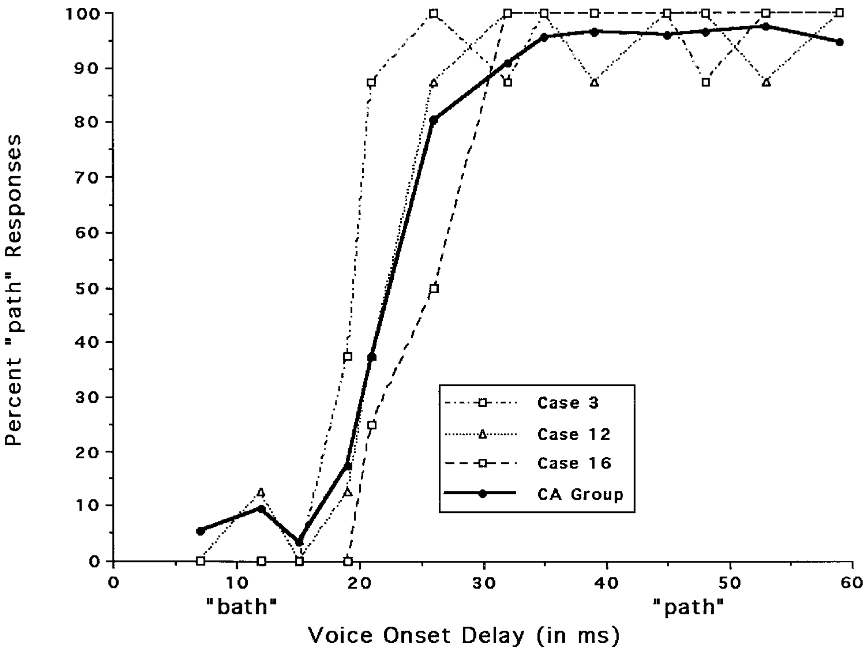

FIG. 3. /b/–/p/ identification functions for three representative normal readers.

responsible for the group and subgroup effects in the study, we show them in Figs. 4–6.

Five of the seven cases (Figs. 4 and 5) were in the low phon. group and two were in the high phon. group (Fig. 6). As is apparent from the figures, the identification functions of the seven varied somewhat. The three children in Fig. 4, who also happened to score the lowest on Position Analysis within the group of seven selected here, appeared not to make a sharp distinction between the /b/ and /p/ ends of the continuum. Their identification functions were strikingly abnormal, in that there was a very gradual and small increase in path responses as the VOT values increased, rather than a sharp categorical distinction. The two cases in Fig. 5 were close to the CA group range on Position Analysis. Case 49 had difficulty at the /b/ end of the continuum and Case 48 at the /p/ end, but the functions were otherwise fairly normal. The two cases with normal phonological awareness shown in Fig. 6 were somewhat different. Case 40 had a normal-appearing identification function with a late transition (at 35–39 ms). Case 47 had wide fluctuations in the percentage of path responses, but the average values for the /b/ (e.g., VOT of 7 to 19 ms) and /p/ (e.g., VOT of 39–59 ms) ends of the continuum were not very distinct. None of the dyslexic cases in Figs. 4–6 had any evidence of hearing loss or history of ear infections according to parental and school reports. The cases shown in Figs. 4–6 are the only dyslexics with abnormal identification func-

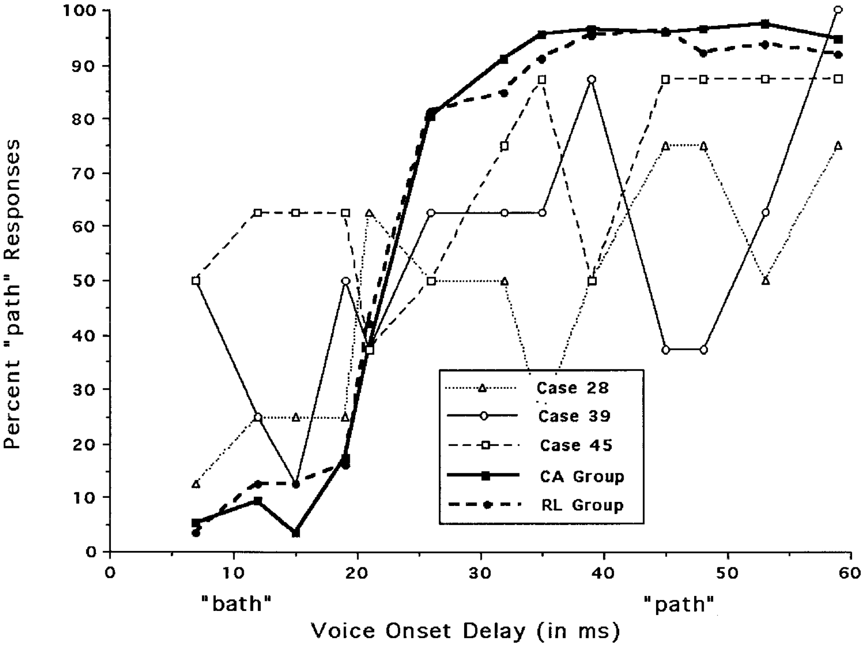

FIG. 4. /b/–/p/ identification functions for the CA and RL groups and three dyslexic cases with low phonemic awareness and poor /b/–/p/ discrimination.

tions. None of the other dyslexic cases in either the low or high phon. groups had unusual difficulty with end points or transition points.

The RL group showed more variability in identification functions than the CA group but less than the dyslexics. Five of the 24 cases had some deviations from strictly categorical perception. Three cases, shown in Fig. 7, showed moderate confusion at the /b/ and /p/ ends analogous to the dyslexic cases in Fig. 4. One child had slight difficulty at the /b/ end and one had a late transition (39–45 ms). These data indicate that some young normal readers show less than strictly categorical perception. Of these five cases, only one scored below the RL group mean on position analysis, suggesting that deficits in speech perception and phonemic awareness were not as strongly associated in this group as they were for the dyslexics. It is possible that some factor other than phonological skill (e.g., attentional factors) accounted for the low performance of these subjects.

DISCUSSION

The results of the study can be summarized as follows. First, overall differences in categorical perception of /b/ and /p/ were found between normal and dyslexic children from comparable grade levels in school, consistent with previous studies of children (Godfrey et al., 1981; Reed, 1989; Werker &

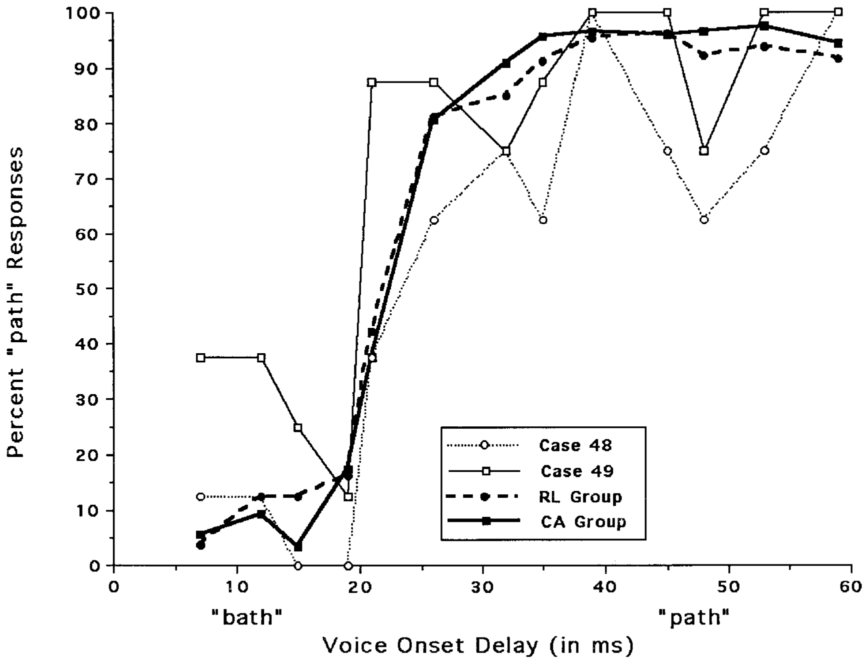

FIG. 5. /b/–/p/ identification functions for the CA and RL groups and two dyslexic cases with low phonemic awareness and poor performance at the /b/ or /p/ ends of the continuum.

Tees, 1987) and adults (Lieberman et al., 1985; Steffens et al., 1992; Watson & Miller, 1993) that used other stop-consonant continua. The group differences were small, as was the case in past studies. Comparisons were also made to a reading level comparison. The RL group did not differ in slope from the dyslexics, although the direction of the difference was the same as that found for the dyslexic-CA group comparison. In part, the small group differences may be due to the fact that memory demands were minimized and the stimuli were presented without any noise. Because the experimental conditions were optimal for making the bath–path discrimination, these deviations from normal performance are noteworthy. However, it is possible that the identification paradigm underestimates the frequency of speech-perception problems. Future studies should include an AX or ABX discrimination paradigm so that more fine-grained discriminations can be tested.

A second major finding was that reader-group differences in categorical perception in the present study were associated with phoneme awareness. Dyslexics with low phonemic awareness had significantly shallower identification functions than both CA and RL groups. Dyslexics with higher phonemic awareness did not differ in bath–path identification from either comparison group. The identification slope differences appeared to be attributable to a small subgroup of dyslexics; the majority of dyslexics in the study had

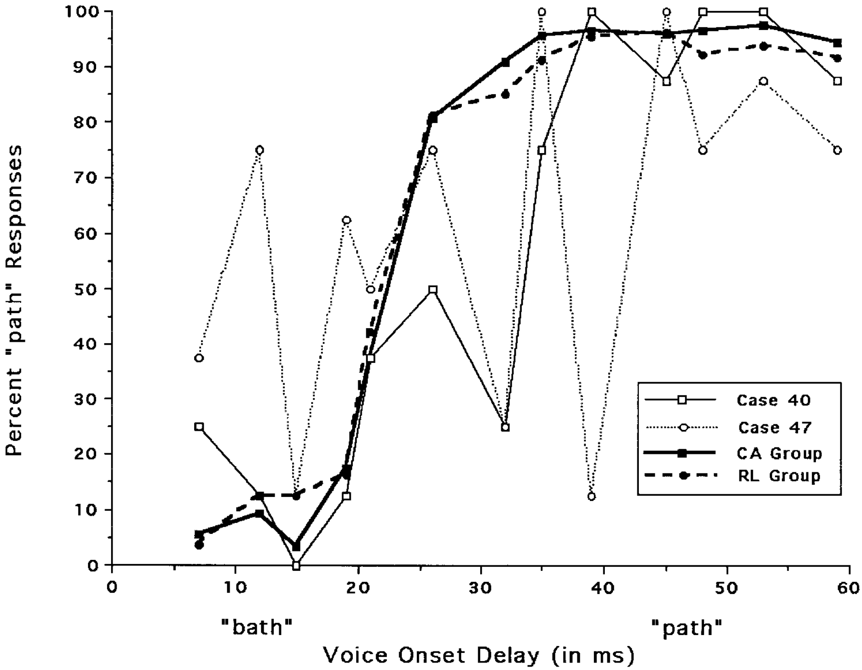

FIG. 6. /b/–/p/ identification functions for the CA and RL groups and two dyslexic cases with aberrant performance and normal phonemic awareness.

normal phoneme-identification functions. Individuals with phoneme-identification deficits were more common in the low phonemic awareness subgroup. The low phon. subgroup was also poorer on the average at nonword reading than any of the other groups in the study, including the high phon. group. This leads to a prediction that children or adults with the phonological dyslexia profile will be more likely to have speech perception deficits than those with other types of reading problems (Castles & Coltheart, 1993; Manis et al., 1996). It is important to point out that the high phonological awareness group was poor at nonword reading relative to the CA and RL groups and thus is not synonymous with a surface dyslexic group. Hence, caution must be observed in generalizing our results to the phonological and surface dyslexic subtypes in the literature. In addition, the finding of a few younger normal readers with deviant identification functions suggests that young and or inexperienced readers have some of the same difficulties in speech perception and phonemic awareness as dyslexic readers.

It must also be noted that more than half of the group with low phonological awareness showed normal phoneme-identification functions. This finding needs to be explored further. One possibility is that a minority of dyslexic children show speech-perception difficulties and that there are alternative

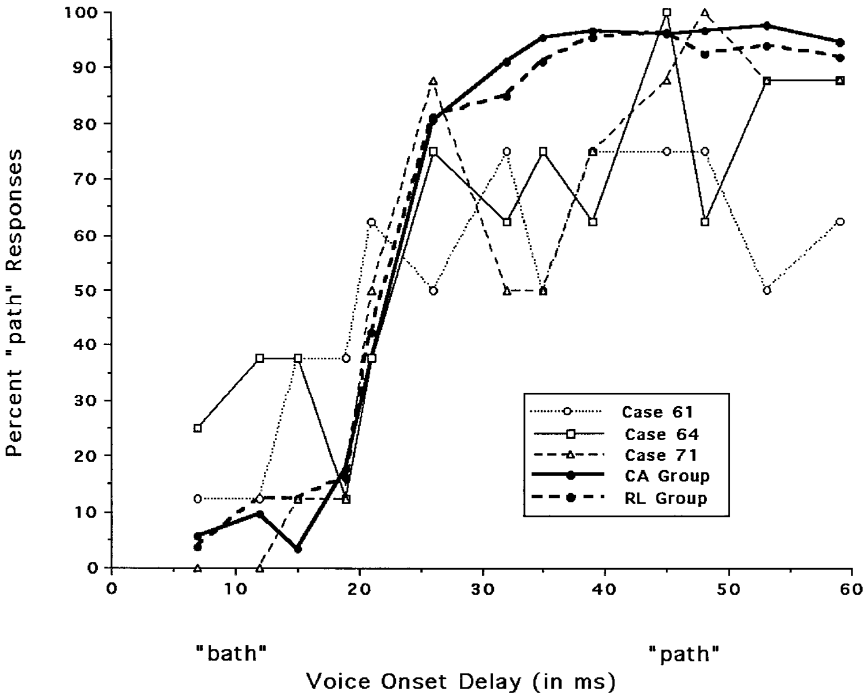

FIG. 7. /b/–/p/ identification functions for the CA and RL groups and three deviant cases from the RL group.

sources of poor phonological awareness. Another possibility is that the perceptual discrimination in the present study was relatively undemanding and hence only sorted out individuals with the most severe impairments. Larger deficits might be observed with more difficult perceptual discriminations such as occur in the AX or ABX paradigms or with other stop-consonant continua. Presenting the stimuli with varying amounts of background noise could also increase the sensitivity of the task in detecting speech-perception problems. Still another possibility is that the size and frequency of speech-perception deficits might have been affected by the choice of an older, highly remediated sample. Hurford and Sanders (1990) provided evidence that phoneme perception varied with age and amount of training. They had success training phonemic discrimination in second-grade poor readers, and found no reader-group differences in their fourth-grade sample. All things considered, the percentage of dyslexics with speech-perception deficits in the present study should be regarded as a conservative estimate of the frequency in the population.

If the differences in speech perception between dyslexics and normal readers are so small that they require subtle manipulations and methodologies to be manifested, why is it important to continue to study them? The fundamental importance of this phenomenon is that a speech perception deficit in dyslexics may have significant long-term developmental and diagnostic implications because of its potential impact on the development of phonemic awareness and on the process of learning grapheme–phoneme correspondences (Manis et al., 1996; McBride-Chang, 1995a; Reed, 1989; Share, 1995; Werker & Tees, 1987). The basic argument is that children who do not perceive clear distinctions between phonemes may not form readily accessible long-term memory representations of these phonemes. This would lead in turn to difficulties in segmenting and manipulating phonemes, and in learning grapheme–phoneme mappings.

Although there is no direct evidence that speech-perception deficits have causal effects on phonemic awareness and reading, structural relationships among these variables in one study (McBride-Chang, 1996) were consistent with this view. McBride-Chang (1996) tested five different structural models of the relations between speech perception, phonemic awareness, and word reading using data from a sample of third- to fourth-grade children representing the full-range of reading ability at that grade level. The best-fitting model was one in which the relationship between speech perception and reading was mediated by phonological awareness. It is possible, of course, that causality runs the other way, i.e., that learning to read refines children's representations of speech.

It must be noted that the data from our study and previous research are not consistent with the idea that a single perceptual deficit accounts for reading problems and language impairments across a broad range of individuals (Farmer & Klein, 1995; Tallal, 1980). Whereas a subset of our subjects exhibited a speech-perception deficit, many dyslexics did not, and some younger normal readers showed mild speech-perception difficulties. Liberman et al. (1985) found speech-perception difficulties in only a subset of their adult dyslexic sample. Further, they found that some dyslexics had difficulties with all of the stop consonants tested, some with only one stop consonant, and some had difficulties only with vowel perception. This suggests that the pattern of speech-perception problems may be quite individualized. Lieberman et al. (1985) did not divide their dyslexics on the basis of other measures of phonological skill. Hence, it remains to be seen whether a consistent relation between speech-perception deficits and phonological-awareness deficits will be found.

An important limitation of this and all previous studies of reader-group differences in speech perception must be considered as well. It is possible that some of the differences between normal and dyslexics in speech perception are attributable to intrinsic differences in attention levels. The finding that larger differences between these groups emerged at the ends of the continua is consistent with various attentional difficulties as well as with misperceptions of speech stimuli. For example, individuals who pay less attention to any type of auditory input may not represent each speech sound in memory as well as those whose attention levels are generally higher. This would produce the pattern of low performance at the ends of the continua, since all subjects (even the CA group) can be expected to find the intermediate stimuli difficult to identify. Future studies should explore attentional deficits as an alternative explanation for these discrepancies in performance.

Another important limitation in our knowledge about speech perception in dyslexia stems from the fact that all extant studies are concurrent rather than prospective. Future research should focus on the importance of early speech-perception abilities. It is possible that speech-perception deficits are more prominent in dyslexic individuals earlier in development. There is emerging evidence that consonant perception in newborns is associated with language competence at age three to five (Molfese, Gill, & Simos, 1995; Molfese & Molfese, 1985; Molfese, Molfese, Benshoff, & Gill, 1993). Given Scarborough's (1990) finding that language competence at age 2 to 3 years is predictive of reading disability at age eight, this raises the fascinating possibility of a predictive relationship between speech perception in early childhood and reading difficulties in school-age children.

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